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Building Blocks for Effective Modeling and Simulation of Systems Lifecycle Using an End-to-End Model-Based Systems Engineering Framework

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ABSTRACT

Model-Based Systems Engineering (MBSE) methodologies, while supplanting document-centric paradigms, exhibit significant implementation challenges. The ontological rigidity of established architectural frameworks (e.g., DoDAF, TOGAF) and the metamodel extensibility limitations of Systems Modeling Language (SysML) impede domain-specific adaptation and model federation. A critical deficiency persists: a semantic gap between the left-side and right-side of the systems engineering V-model. This decoupling results in a fractured digital thread and costly, late-stage error detection. This paper posits the conceptual architecture of the "End-to-End Model-Based Systems Engineering (E2E-MBSE) Framework," a novel solution designed to rectify these lifecycle integration failures. The proposed E2E-MBSE Framework aims to address the limitations of existing frameworks by providing a modular, pattern-based approach utilizing a library of reusable and scalable SysML packages. This structure provides a customizable "toolkit" rather than a rigid, monolithic standard, allowing practitioners and researchers to tailor the methodology to specific industry applications or domain-specific needs. Crucially, the framework is predicated on formal semantics and integrated APIs integration providing a technical backbone for developing a "Total System Model" (TSM) that serves as a single source of truth and evolves throughout the system's entire lifespan. Instead of treating Verification and Validation (V&V) as discrete, late-stage activities on the right side of the V, the framework leverages real-time traceability capabilities to embed automated, continuous V&V directly within the modeling process, creating a living "digital thread" that ensures traceability and consistency.

Keywords: End-to-end model-based systems engineering (E2E MBSE), Systems modeling language (SysML), System architecture, MBSE framework, Verification and validation (V&V), Digital engineering

INTRODUCTION

Systems Engineering Vee Model

The Systems Engineering Body of Knowledge (SEBoK) defines model as a "physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process" (SEBoK, 2024). Systems Engineering (SE) Vee or V model is one of the ways to represent a system lifecycle. The V model is the approach with pre-specified and sequential processes (Fairley et al., 2024). There are several life cycle process models that are categorized into the following three primary categories: (1) primarily pre-specified single-step or multistep, also known as traditional or sequential processes; (2) evolutionary sequential (or the V Model) and (3) evolutionary opportunistic and evolutionary concurrent (or incremental agile)" (Fairley et al., 2024). At a macro level, the SE V generates system-level specifications decomposition and plans for eventual Verification and Validation (V&V). Which advances from the lowest-level implementation to the next-level up, subsequent subsystem-levels, and finally to the system-level for realization, as illustrated in Figure 1 below.

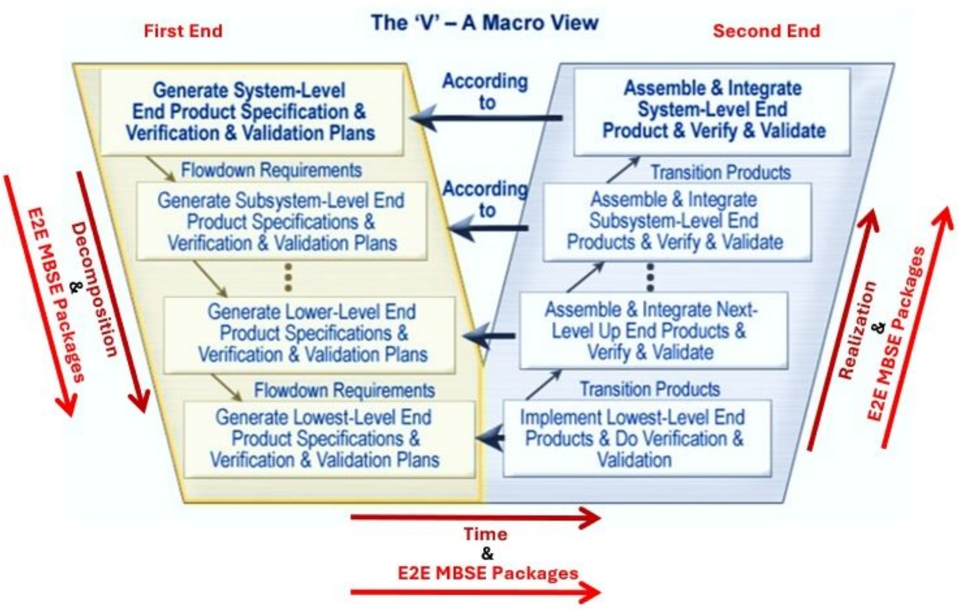

Figure 1: SE V Macro View. (Forsberg et al. 2005, adapted by Prosnick, 2010. Adapted and modified from Coronel Mariño, 2017.)

Model-Based Systems Engineering (MBSE)

Model-Based Systems Engineering (MBSE) has become a cornerstone of modern SE, enabling complex system design, analysis, and lifecycle management through standardized modeling methodologies. MBSE is a "formalized application of modeling to support system requirements, design, analysis, verification & validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (SEBoK, 2024). When there is a stakeholder requirement for the design of a System of Interest (SoI), MBSE facilitates the modeling and simulation of the system in a digital realm before, during, and as the product (physical or digital) is developed. Traditionally these SoI frequently utilized a document-centric approach prior to MBSE. "The evolution from "document-centric" to "data-centric" and "model-centric" information leveraging structured data and model-based approaches is at the heart of Digital Engineering (DE) transformational efforts underway across industry and government" producing "Authoritative Sources of Truth (ASOTs), and systems-of-systems interoperability" (DiVenti et al., 2023). Nevertheless, "it is noticeable that, there is a lack of a common understanding for how formal analyses for the V&V of systems behaviour, specifically in the early phases of system development, could be placed in an MBSE setting" (Cederbladh et al., 2024).

Problem Statement

Organizations and institutions seem to succeed at the left side of the SE V model from requirements development up to integration but struggle to make the successful transition to model-based verification and validation on the right side of the V model in MBSE (Adelabu and Lohar, 2025a). Existing frameworks are fragmented and piecemeal at times. There are V&V efficacy needs with accompanying challenges such as complexity of models, resource constraints, integration issues, tool and methodology gaps, and requirement traceability issues; as a result, research work needs to define new SE and V&V concepts (Laing et al., 2020). "Traditional MBSE approaches are often distributed across multiple stages and tools" resulting in fragmentation of system architecture, physical modeling, and performance optimization, with limited real-time coordination and feedback (Zhang et al., 2025).

Proposed Solution

The concept of an E2E-MBSE Framework possesses the potential to solve a host of the aforementioned problems from the lack of an E2E-MBSE Framework, which has led to use of piecemeal frameworks, to the Valley of Death (VoD), traceability, and integration issues. The ability to develop, design, integrate, test, verify, validate, maintain, and plan for the retirement or end-of-life of a system prior to its digital or physical development is of immense value. The transition from document-centric to model-centric offers distinct advantages, including several key benefits such as, "increased data availability, data access equity, data traceability, real-time analytics, batch analytics, and (most importantly) acceleration of the time-to-value and time-to-insights associated with engineering products and analyses" (DiVenti et al., 2023). These engineering products and analyses range from SE artifacts to products produced from SE application, and analyses such as Stakeholder Analysis, Trade Studies Analysis, Functional Analyses, etc. These data must be traceable and offer real-time model representation. "The longer-term benefits of reusability, customization and traceability are even more promising" (DiVenti et al., 2023), and the realization of those benefits is crucial in providing systems engineers with "vital information when needed to support critical decision-making throughout the entire life cycle" (DiVenti et al., 2023). As a result of the applicability to decision-making throughout the entire SE V and systems lifecycle or life cycle, the E2E-MBSE Framework fits perfectly in enabling such decisions and capitalizing on those needed benefits.

LITERATURE REVIEW

Left to Right Side of SE V and Life Cycle Cost Implications

When developing the left side of the V, considerations that should have been modeled from the inception of the system are left out due to omission or lack of knowledge and or awareness (Coronel Mariño, 2017), (Cederbladh et al., 2024). Systems engineers, modelers, and practitioners forget to model things on the left side that are essential for V&V on the right side, and it costs resources (both money and time) to go back and rectify issues and provide new information that should have been captured in the first place (Cederbladh et al., 2024), (Laing et al., 2020).

Lack of End-to-End Framework

"There is a gap in the common understanding of where MBSE models end and start, in addition to what can be considered a "good enough" model at various stages of development" (Cederbladh, 2024). "Limited guidance exists for implementing V&V in a model-based environment, particularly for early lifecycle activities" (Mulholland et al., 2025). Frameworks or methodologies concentrate on conceptual and detailed design activities (Delligatti, 2014) (Friedenthal, 2017) (Friedenthal S. M., 2015). Some approaches concentrate on the left portion of the SE V model and offer only minimal advice on how MBSE supports needs, requirements, and system V&V tasks (Wilson-Smith and Kibler, 2016).

Advancement of Rule of Thumb to Principles to Framework

A rule of thumb is a guiding principle that informs decision-making, and may, in certain cases, clarify operational mechanisms. Principles offer direction or boundaries for the design and development of systems, ensuring stakeholders' needs and functions are met within the given context or intended environment. It is important to note, however, that principles alone do not constitute frameworks, and practitioners should recognise the necessity for practical implementation beyond establishing principles. An architectural framework is defined as "Conventions, principles, and practices for the description of architectures established within a specific domain of application and/or community of stakeholders (SEBoK, 2024). In essence, a framework encompasses architectures and provides descriptions of those architectures within its structure. This leads to the question: what precisely is architecture? The definition of architecture varies from an art and practice of designing and building structures, formation, or construction that can include patterns as the result of a conscious act, a unifying or coherent form or structure, etc. (Lohar, 2022) while an Architectural Description (AD) is work product used to express an architecture (ISO, 2022).

Frameworks can be developed to execute and incorporate SE principles, can have various architectural constructs, and can simultaneously consist of diverse concepts. Concepts like modularity, scalability, integration, and the balance between performance, cost, and risk are guided by SE principles as well as the manufacturability of designed systems due to the migration from mass customization to mass personalization resulting in increased complexity, and as a result need to be guided and gives the rise to modularity or modular design (Roy and Abdul-Nour, 2024). However, principles are not enough for effective design and or understanding of a system. There is a need for a framework that has end-to-end building blocks (Adelabu and Lohar, 2025c).

Existing Frameworks

Traditional frameworks below address select components of the SE V model:

1) Federal Enterprise Architecture Framework (FEAF) (TOGAF, 2019)
2) Department of Defense Architectural Framework (DoDAF) (OMG, 2025)
3) The Open Group Architectural Framework (TOGAF) (TOGAF, 2019)
4) ARChitecture Analysis and Design Integrated Approach (ARCADIA) (Voirin, 2025)
5) Unified Architecture Framework (UAF) (OMG, 2025)
6) Mission Architecture Framework (MAF) (NASA, 2021)
7) MOFLT (Cortier et al., 2022)
8) Model Based Mission Assurance (MBMA) in a MBSE Framework (Cornford and Feather, 2016)
9) Modular Open Systems Approach (MOSA) Framework (DoD / DoW, 2020)
10) NASA-STD-7009A Models & Simulations (M&S) Life Cycle (NASA, 2019)
11) Zachman's Framework, (Uzhakova and Fischer, 2024) etc.

Several of these frameworks are mainly Enterprise Architectural Frameworks (EAF), incorporate certain SE elements, and include model-based components or direct support for MBSE. However, addressing only segments of the SE V significantly lacks a thorough and effective MBSE framework that systems engineers can reliably use throughout the entire SE V process.

Table 1 above shows the low scoring nature of some of the frameworks in domain support and modeling language openness, making them non-versatile.

Table 1: Comparison of selected frameworks (Bankauskaite, 2019).

EAF / Criteria	DoDAF	NAF	MoDAF	UAF	FEAF	TOGAF
Domain Support	1	1	1	3	1	2
Modeling Language Openness	1	1	1	4	1	1
Information Availability	3	2	3	1	1	4
Tool Support	3	3	3	2	2	3
Prevalence by Researchers	4	2	3	1	1	4
TOTAL	1.9	1.6	1.8	2.8	1.2	2.3

Understanding frameworks, architectures, concepts, properties, and other elements of SE is crucial to the development of an E2E-MBSE Framework. The present limitations of existing frameworks can be categorised into three main areas: (i) The presence of fragmented individual frameworks covering certain aspects on the left side of the V, which in some instances, begin at the mid to lower sections of the V, thereby omitting the initial stages necessary for a comprehensive understanding of the system, including its interests, perspectives, stakeholder desires, and related factors (Zhang et al., 2025). (ii) Limited to no framework for the right side of the V (Cederbladh et al. 2024). (iii) There is no established framework to transition from the left to the right side of the V and overcome the VoD. This research seeks to provide the framework to address all three prongs.

EXPERIMENT AND DISCUSSION

Rationale for Research Methodology

This research extends comprehensively across the entirety of the V model, both from a framework perspective and throughout the developmental phases of the SoI. After thorough evaluation of the available materials, it became evident that employing a single research methodology would be insufficient to capture, analyze, and develop the foundational building block elements necessary for an "End-to-End Model-Based Systems Engineering (E2E-MBSE) Framework". As a result, a combination of research methodologies is utilized, infusing strengths, shoring up weaknesses by another method's strength, and ensuring applicability to a model-based approach.

Research Methodology

This research utilizes the Complex Observation Mixed Methods Explication Case Study (COMMECS) design (Adelabu and Lohar, 2025b).

1) Complex or Complexity Theory, because the field of MBSE and SE in general is complex domain; the SoI are complex; complexity addresses complex research questions that require multiple perspectives and methods,
2) Observation, because it entails observation methodologies,
3) Mixed Methods, because it includes both Quantitative & Qualitative methods,

4) Explication or Explication Theory, because traditional MBSE frameworks and the E2E-MBSE Framework are explicated to the SE V model, and
5) Case Study, because the chosen system of interest will be the Proof of Concept (PoC) for the E2E-MBSE Framework.

Research Procedure

The proposed COMMECS design for research follows the steps below:

1) Identify common terminologies and architectures across frameworks,
2) Determine which architectures are shared or unique across the frameworks,
3) Define the beginning and end points of the frameworks,
4) Detect gaps between those ends,
5) Propose new architectures and building blocks to address identified gaps,
6) Link all building blocks from one end of the frameworks model to the another.

At first, common terms and structural patterns from different frameworks are mapped out, accounting for variation in terminologies or differences in taxonomies. Next, widely used architectures are analyzed to uncover gaps that need addressing, which resulted in new architectural development to bridge those gaps. The resulting building blocks are then linked together, and this process continues until every essential connection within the E2E-MBSE Framework is completed.

Results

A preliminary outcome of the experiment provides a high-level overview of various established MBSE frameworks and their respective components. These frameworks primarily address elements situated on the left side of the SE V, as illustrated in the table below.

Table 2: Some existing frameworks' building blocks for SE.

SOME EXISITING FRAMEWORKS' BUILDING BLOCKS FOR SE							
	UAF	SMAF	ARCADIA	MOFLT	MBSE in S&MA	MOSA	NASA-HDBK-7009A M&S
BUILDING BLOCKS	Architecture Drivers & Challenges	Science Needs, Goals, and Objectives	Operational Analysis	Mission Architecture	Objectives / Mission	Stakeholder	Conceptual Studies
	Enterprise Strategy & Capabilities	Mission System Architecture	System Need Analysis	Operations Architecture	Requirements	Requirements	Concept & Technology Development
	Operational Architectures	Project/Management	Logical Architecture	Functional Architecture	Structure	Technical Architecture	Preliminary Design & Technology Completion
	Service Architectures	Resources – Current and Planned	Physical Architecture	Logical Architecture	Behavior	Modular Architecture	Final Design & Fabrication
	Resource Architectures	-	Components Requirements	Technical Architecture	-	Physical Architecture	System Assembly, Integration, & Test
	Personnel Architectures	-	-	-	-	-	Operations & Sustainment
	Security Architectures	-	-	-	-	-	Closeout
	Projects Portfolio Management	-	-	-	-	-	-
	Resource Realization	-	-	-	-	-	-

The common building blocks in each observed framework were color-coded, while uncommon ones were not. When the question is asked to develop a SoI from end-to-end, both recent SE graduates and experienced practitioners face challenges in using these frameworks directly to create a SoI throughout its lifecycle. This highlights the need for an E2E-MBSE Framework to address existing knowledge gaps and viewpoints of the different SE modelers, engineers, architects, and practitioners.

CONCLUSION AND FUTURE WORK

This paper presents the conceptual design of an innovative E2E-MBSE Framework, which addresses the persistent challenges in applying existing frameworks across the full system lifecycle. A recent graduate, an emerging system engineer with limited to no experience and a systems engineer with decades of hands-on SE experience (traditional), would be able to use the proposed E2E-MBSE Framework because it not only resolves some of the pain points discussed in this paper but also allows them to communicate their viewpoints for the successful development of SoI. Furthermore, future work will include documentation (a user guide) that walks the user (whether novice in SE or a subject matter expert) through description of each of the proposed 24 building blocks packages and how to utilize them, providing the walkthrough needed for users. Also, a demonstration of the application of each of the 24 proposed building blocks that assists a user from one end of the SE V to the other end for a chosen SoI will depict or show PoC and or application.

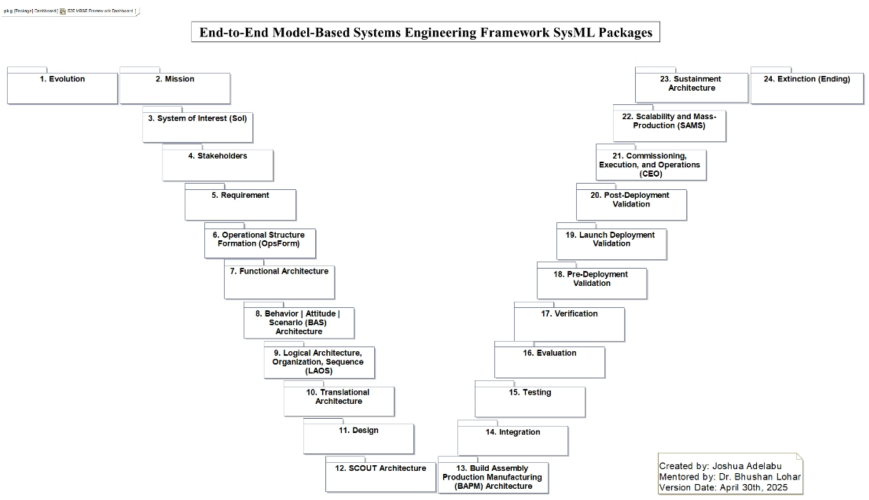

Figure 2: End-to-end MBSE framework packages with the 24 building blocks.

The concept of duality in personality, akin to the wave-particle duality in quantum mechanics serves as an additional rationale for adopting the E2E-MBSE Framework, both from the perspective of a recent graduate entering systems engineering domain and that of an experienced industry practitioner.

This duality reflects the fusion of two distinct viewpoints, each informed by firsthand exposure to relevant environments, resulting in motivation applicable to a wide range of users. Accordingly, the authors aim to deliver a solution that meets the needs of both perspectives by ensuring the framework is effective, efficient, and user-friendly.

While MBSE is a promising alternative to traditional document-based approaches, its industrial application remains limited by the rigidity and domain-specific nature of the current frameworks, which often fail to provide a cohesive approach from a system's inception to its disposal. The proposed E2E-MBSE Framework is architected as a next-generation solution, designed to overcome limitations in Industry 5.0 by offering a structured, model-centric approach to address core challenges like integrating human-centric design, empathic design, promoting sustainability, and enhancing resilience. The framework's core innovation is a modular, pattern-based approach that utilizes a library of reusable and scalable SysML packages (Lohar, 2022). This structure provides a customizable "toolkit" rather than a rigid, monolithic standard, allowing practitioners and researchers to tailor the methodology to specific industry applications or domain-specific needs. Crucially, the framework is predicated on the foundational capabilities of a standalone architecture, with formal semantics and integrated APIs integration providing a technical backbone for developing a "Total System Model" (TSM) that serves as a single source of truth and evolves throughout the system's entire lifespan. This approach fundamentally redefines the relationship with the systems engineering V model. Instead of treating V&V as discrete, late-stage activities on the right side of the V, the framework leverages real-time traceability capabilities to embed automated, continuous V&V directly within the modeling process.

This creates a living "digital thread" that ensures traceability and consistency from requirements decomposition to sustainable system retirement, thereby significantly reducing project risk and enhancing operational efficiency. The research outlines the framework's architecture, its foundational principles, and its potential to revolutionize systems engineering by providing a flexible, scalable, and verifiable methodology for the complex systems of the future. Future work includes analysis of one or more of these 24 building blocks and a SoI for PoC.

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